In-flight verification of the FREGATE spectral response

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Abstract.
We present the first results of the in-flight validation of the spectral response of the FREGATE X/γ detectors on–board the HETE–2 satellite. This validation uses the Crab pulsar and nebula as reference spectra.

INTRODUCTION

The four identical FREGATE X/γ–ray detectors onboard HETE-2, are sensitive to photons between 6 and 400 keV (see [1] for a full description of the experiment and operating modes). In this short paper, we describe briefly the Monte Carlo simulations of the detectors, the ground calibrations, and the validation of the in-flight performances using the Crab pulsar and nebula as standards. We compare the spectral parameters obtained with FREGATE with those reported by other instruments in similar energy ranges.

SIMULATIONS AND CALIBRATIONS

In parallel with the construction of the detectors, the energy response matrix of FREGATE was calculated from extensive Monte Carlo simulations of the detector using CERN's GEANT package. More than 50 regions of different materials were included in the simulation with special care for the regions in the detector field-of-view (e.g. the graded shield and the beryllium window). The parameters (position, angles, energy, etc.) of the incoming photons are generated within a separate code including several options (point-like radioactive source at a finite distance with several photons and branching ratios, parallel flux for celestial sources, etc.). Once the photon characteristics are generated, the tracking code is the same in all cases. The Monte-Carlo simulations were checked before launch with the help of ground calibrations using a large set of radioactive sources (9 sources with photons energies spanning from 8 to 1300 keV) and angles of incidence from on-axis to 60° in 5° steps. We have first determined realistic gains and resolutions for our detectors. Then, the simulated spectra

(in a point-like configuration) have been folded with the detector response functions and normalized knowing the source activity for the given energy, the duration of the calibration run and the solid angle presented by the detector to the photon flux. Finally, we compared the simulated spectra with those from the calibrations. For all angles and energies, we found that the relative differences in the full energy peak and in the diffusion continuum were less than 10 %, which is on the order of the uncertainties of the source activity (see Figure 1 for few examples of comparison). Since we concentrate in this paper on the validation of the in-flight performances, we will not discuss these comparisons any further.

IN-FLIGHT CALIBRATIONS

Since launch, the gains of each detector have been continuously monitored using on-board calibration ^{133}Ba sources (two lines at 81 and 356 keV). The positions of these lines show a weekly orbital variation of a few percent, and a long-term drift on a ~ 100 day scale periodically corrected by adjusting the high voltage commands. No significant variation of the relative line width has been found. These in-flight calibrations are used to find the correct channel-to-energy relations during the HETE mission. FREGATE generates two types of scientific data with good spectral resolution : permanently the 'Spectral Data' (**SD**: four 128 channel energy spectra every 5 or 10 seconds); and when a trigger occurs : the 'Burst Data' (**BD**: 256k photons tagged in time with a resolution of $6.4\,\mu$s in time and in 256 channels in energy). The process of spectral deconvolution for both data types has been tested during the in-flight verification phase, using the Crab pulsar (for the BD) and nebula (for the SD). The counting rates in the 6–200 keV range obtained from the
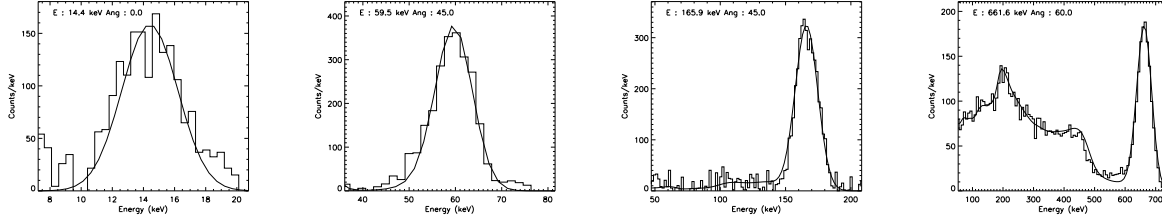
FIGURE 1. Comparison of experimental spectra of several radioactive sources from ground calibrations (histograms) and the corresponding simulated spectra (solid lines). From left to right : ^{60}Co (14 keV, 0°), ^{241}Am (59 keV, 45°), ^{139}Ce (166 keV, 45°) and ^{137}Cs (662 keV, 60°). The simulations are normalized using the source activity for the given energy, the duration of the calibration run, and the solid angle of the detector seen by the source. In other words, it is an absolute comparison.

four detectors have been rebinned in the same histogram to improve the statistical significance. We have checked that fitting the four spectra simultaneously gives the same spectral parameters within the error bars. As usual for the Crab, we used a single power law model :

$$\frac{dN}{dE} = A_{30}\, E_{30}^{-\gamma} \,\mathrm{ph\ cm^{-2}\ s^{-1}\ keV^{-1}} \qquad (1)$$

where E_{30} is defined as $E_{30} = E/30$ keV

The Crab pulsar

The data consist of 10 artificial burst triggers recorded on 01/07/2001, when the Crab was about 23° off axis. Considering that the triggers are separated by only a few minutes, the photon times were not barycenter corrected. We have constructed the folded light-curves (with a 33 phase bin epoch folding) for periods around the expected Crab period ([3]). For each light-curve, we have computed the χ^2_{red} value. For the maximal value of this statistical parameter ($\chi^2_{red} = 10.1$) we have found the best pulsation period (ν =29.832951 Hz). This value is $\sim 10^{-3}$ Hz smaller than the extrapolated value from the ephemeris (ν_0 =29.834086 Hz) which is compatible with a Doppler shift due to the earth's motion in the solar system and the satellite motion in its orbit. The corresponding phasogram (Figure 2) consists of two peaks of similar intensity, separated by ~ 0.4 in phase and connected by an interpulse. Even if the peaks are a little broad (due to the lack of barycentric corrections), this phasogram looks very similar to the ones reported at X and γ energies. The off-pulse level and spectrum were obtained for phases outside the pulsed emission (dashed level, Figure 2).

We obtained a good fit with the spectral model described above ($\chi^2_{red} = 1.1$ for 86 dof). The rebinned unfolded spectrum can be seen in Figure 4. The spectral parameters are reported in Table 1. The spectral index (1.87 ± 0.13) is fully consistent with those reported in similar energy ranges. The amplitude (A_{30}) is about 10 %
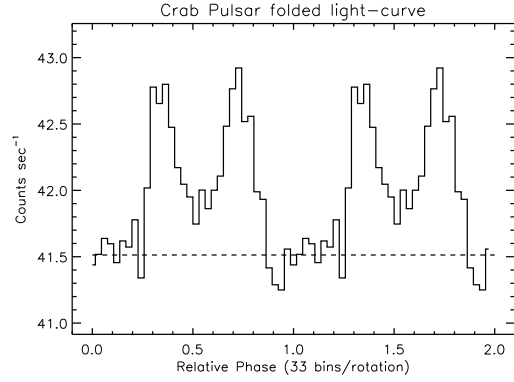

FIGURE 2. The Crab pulsar light-curve folded at the best pulsation period. Two periods are shown.

lower than the canonical value (although roughly consistent within the error bars). This can be explained because, in absence of timing corrections, the FREGATE light curve is smoothed and our definition of the total pulsed interval (0.6 in phase) is greater than the one usually used (~ 0.5-0.55).

The Crab Nebula

The Crab was periodicaly occulted by the Earth in the FREGATE field-of-view with an inclination angle less than 10° on December, 2000. The occultation dates (Crab rise and Crab set) were calculated. From the SD, we have extracted sets of 80 successive spectra centered on the occultation dates. With a screening procedure, the data polluted with solar flares or high background were eliminated, leading to 90 'good' occultations. Then we have added all these 90 occultations (spectrum by spectrum), to get an 'averaged' set of 80 successive spectra centered on the Crab steps (a Crab set is time-reversed before

TABLE 1. Summary for Crab pulsar and Crab nebula spectral parameters (FREGATE results and [5]). The spectral index is represented by γ. The parameter A_{30} (intensity at 30 keV) is in units of 10^{-3} ph cm^{-2} s^{-1} keV^{-1}. While given by the authors at a different energy, this amplitude has been recalculated using the quoted best-fit slope.

Reference	Energy range	Pulsar (phase averaged)		Nebula (total emission)	
		A_{30}	γ	A_{30}	γ
FREGATE	6-200 keV	**0.89 ± 0.13**	**1.87 ± 0.13**	**7.23 ± 0.2**	**2.16 ± 0.03**
[5]	15-130 keV	1.04	2.06 ± 0.3	7.05	2.18 ± 0.04
[2]	15-180 keV	–	–	7.46	2.06 ± 0.01
[4]	20-200 keV	1.06	1.92 ± 0.09	7.48	1.94 ± 0.02
[6]	20-250 keV	1.16	1.96 ± 0.05	7.18	2.19 ± 0.02

adding). Next, the light-curve for each of the 128 energy channels has been fitted with a polynomial function of fourth degree to account for the background orbital variation plus a centered step to account for the Crab contribution in the channel (see an example in Figure 3). Thus, the Crab spectrum is built channel-by-channel for each of the four FREGATE detectors.
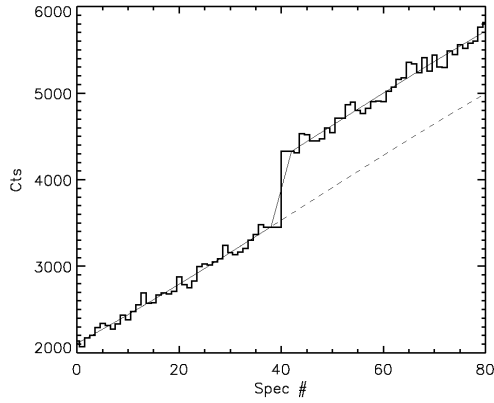

FIGURE 3. Exemple of light curve obtained by folding the Spectral Data of FREGATE with respect to the Crab occultation times. The amplitude of the step represents the number of counts due to the Crab nebula.

Again, we obtained a good fit with a power law model ($\chi^2_{red} = 1.19$ for 84 dof, $\gamma = 2.16 \pm 0.03$) with spectral parameters fully consistent with those reported in similar energy ranges (see the unfolded spectrum in Figure 4 and the parameters in Table 1).

CONCLUSION

For both the Crab pulsar and nebula spectra, the spectral parameters derived with FREGATE are fully consistent with the canonical values. This demonstrates our capability to perform a detailed spectral analysis of sources within the FREGATE field-of-view, even for low statistics spectra such as the pulsed spectrum presented here.
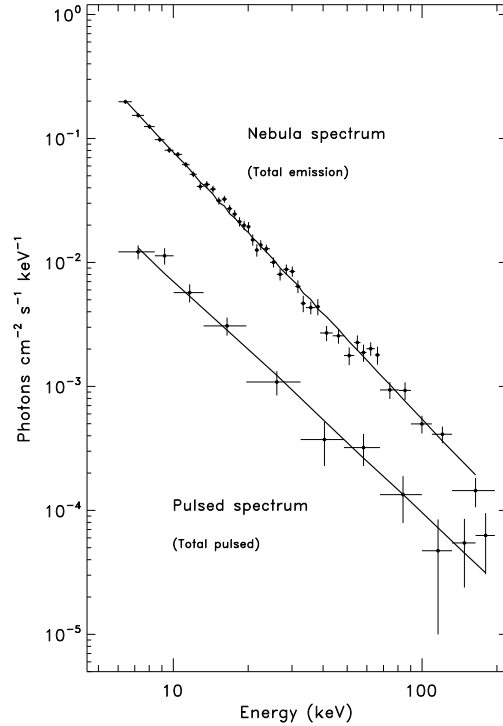

FIGURE 4. Unfolded spectrum of the total nebula emission and the phase averaged Crab pulsed emission

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